Shape optimization design and material selection for a fitness equipment

Ruoxu Jia1, Junling Hu1, Xingguo Xiong2, and Linfeng Zhang2
Department of Mechanical Engineering, University of Bridgeport

Abstract

Recently, engineers still pay attention to the design of bar structure. For their simple shape and simple manufacture process, a lighter and cheaper bar structure was demanded. As the bar structure is used widely in people's daily life, there is a fairly useful example for bar structure design. In this project, the Finite Element Method (FEM) was applied to design the bar structures of the fitness equipment. The principle stress and deformation of the equipment by a load that simulate the body weight was predicted by the FEM software (ANSYS). According to the result, the requirement of the material properties was found. The Yield Stress must be lower than the maximum stress, which means this equipment will not be broken at the load. The thickness of the bar and the maximum principle stress was set for a parametric study. For this step, the minimum volume was found. There are many different ways to select an appropriate material. In this project, the CES Edupack was used to select the material.

Introduction

Engineers face constant challenge to design a product or system with low weight, low cost and good performance. A key objective of mechanical engineering design is to define the dimensions of a component and the materials from which it is made so that it can perform a function acceptably and economically. Optimum design of a product is the selection of the geometry, material and manufacturing process to meet design requirements and maximize its performance and minimize its cost .

There are three aspects to consider in the geometry design of structure a product: (i) topology, which concerns the number and connectivity of members; (ii) shape, which pertains to the location of structural joints; and (iii) sizing, which involves defining member cross-sections. The specification of each aspect of the structure typically corresponds to the three major stages of the engineering design process as defined by Pahl and Beitz: conceptual, embodiment (design development) and detail. The topology of the structure is typically identified during conceptual design based on the functional requirements and architectural aesthetics, whereas the structure' s shape and member sizing are determined during the design development and detailed design phases, respectively.

Materials and process information is needed at every design stage. Material identification at the early design stage need approximate data for all materials and processes and material selection at the final detail stage need to consider precise and detailed data for one or a few materials and processes. There are tens of thousands of materials and hundreds of manufacturing processes to be chosen to shape, join and finish for a product. Mechanical engineers either assume a material before optimizing the geometry or select the best material for an existing geometry of a structure, but neither approach guarantee the optimal combination of geometry and material. Many optimization methods have been developed to integrate geometry design and material selection. However, these methods are only for simple systems.

Extensive research has been devoted to develop various material selection methods. Ashby etc. have developed materials strategies for materials and processes. They presented four steps to choose materials and processes for design requirements: (1) translating design requirements into a specification for material and process; (2) screening out those that cannot meet the specification; (3) ranking the surviving materials and process and identifying those have the greatest potential; (4) searching for supporting information about the top ranked candidates, such as case studies of their use to know their strengths and weaknesses. The key part of the material selection process is screening and ranking of solutions. There is an increasing use of computer tools to help manage the large amount of information and to implement selection strategies, particularly for multi-criteria decision making.

In this project, Ashby's material selection strategy is used to choose material and manufacturing processes for a wall mounted pull up bar structure. A computer aided material selection software package CES Edupack is used to select the material and process for the bar structure. The structural analysis of the bar structure is carried

Problem Specification

The project adopted a wall mounted pull up bar model from Ultimate Body Press, as shown in Fig. 1. The bar structure consists of two reinforced heavy duty beams with a grip at each end and a pull up bar with four grips. As the most important component of this structure is the supporting beam, this paper presented the structural design and material selection of a supporting beam which is designed to support a body weight of 250 lb applied at the grip handle 20 in away from wall.

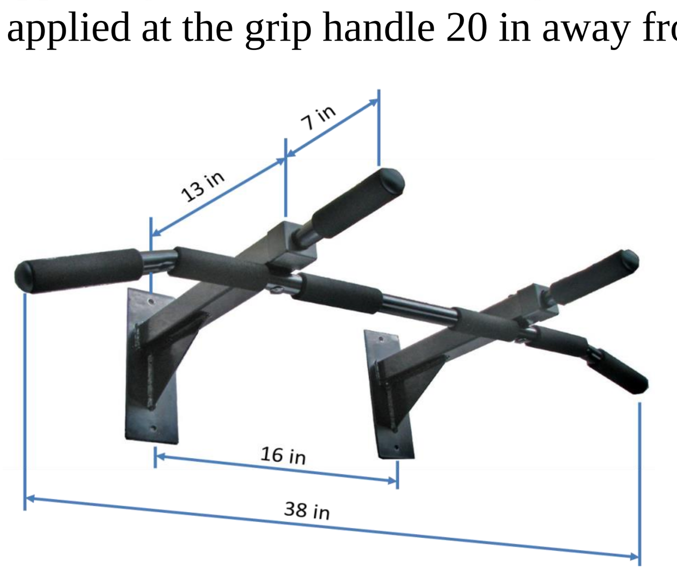

Fig. 1. The wall mounted pull up bar model adopted for this design

Selection of Material

Table 1. Translation of Design requirements

Function	Beam to resist bending load
Objective	Minimize mass and material cost
Constraint	Load F is specified Length L is specified as
Free variables	Material choice Cross section shape

TABLE II PROPERTIES OF LOW ALLY STEEL

Properties	Symbol	Value	Unit
Density	ρ	7800 - 7900	kg/m^3
Price	C_m	0.54 -0.60	\$/kg
Young's modulus	E	206 - 216	GPa
Poisson's ratio	ν	0.285 - 0.295	
Yield strength	σ_y	1840 -2260	MPa

The supporting beam can be modeled as a cantilever beam with a standard squire cross section of thickness *b* and length *L*, as shown in Fig. 3. The design requirements are summarized in Table I.

A penalty function is constructed for the optimization with two conflicting objectives. $Z_p = \frac{\rho}{\left(\sigma_y \phi_B^f\right)^{2/3}}(C_m + \alpha)$

where α is the exchange constant, which measures the value of performance. Three exchange constants are used to represent three cases, 0.1\$/kg for weight is a less concern compared to cost, 1\$/kg for weight and cost are equally important, and \$10/kg for weight is more important than cost. The penalty functions for the three cases are plotted in CES and the best sets of materials are shown in Fig. 4. The plots does not include shape factor in the penalty function. As it can be seen in Fig. 4 that the best material for a cheap pull up bar is high carbon steel, for a light and cheap bar is low alloy steel, and a light bar is wrought magnesium alloy or CFRP.

As the wall mount pull up bars do not need to be portable, cost is equally or more important than weight. Therefore, low alloy steel is chosen as the material for the pull up bars. Further selection with CES level 3 materials gives the best material as AISI 9255 low alloy steel. The properties of this steel is listed in Table II.

Selection of Shape and Size

In order to get an accurate stress when a load is used, the static structure analysis is conducted in ANSYS Workbench. The surfaces of the fixtures connected to wall have a fixed boundary condition. A 250 lb. load is applied on each bar.

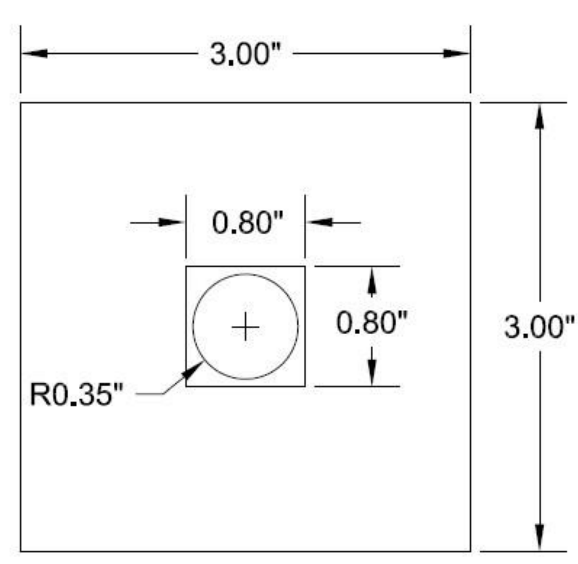

Fig.2 Dimension of bars

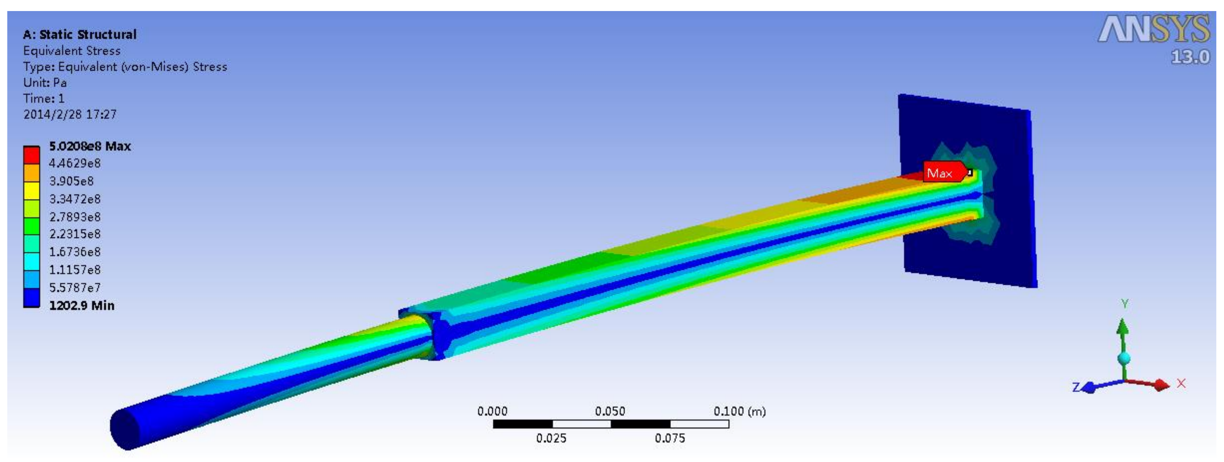

Fig.3 distribution of Equivalent (von-Mises) stress

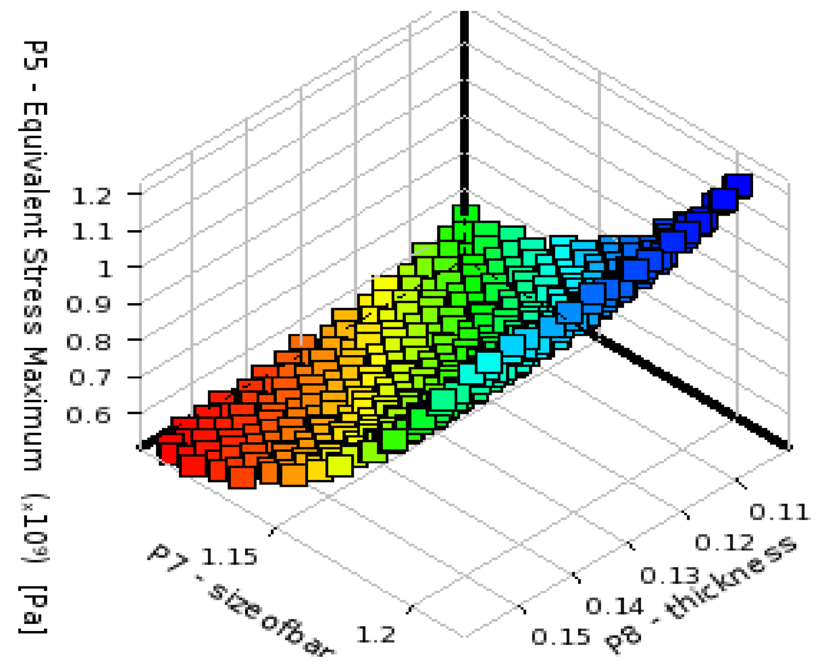

Fig.4 Tradeoff of Equivalent (von-Mises) stress

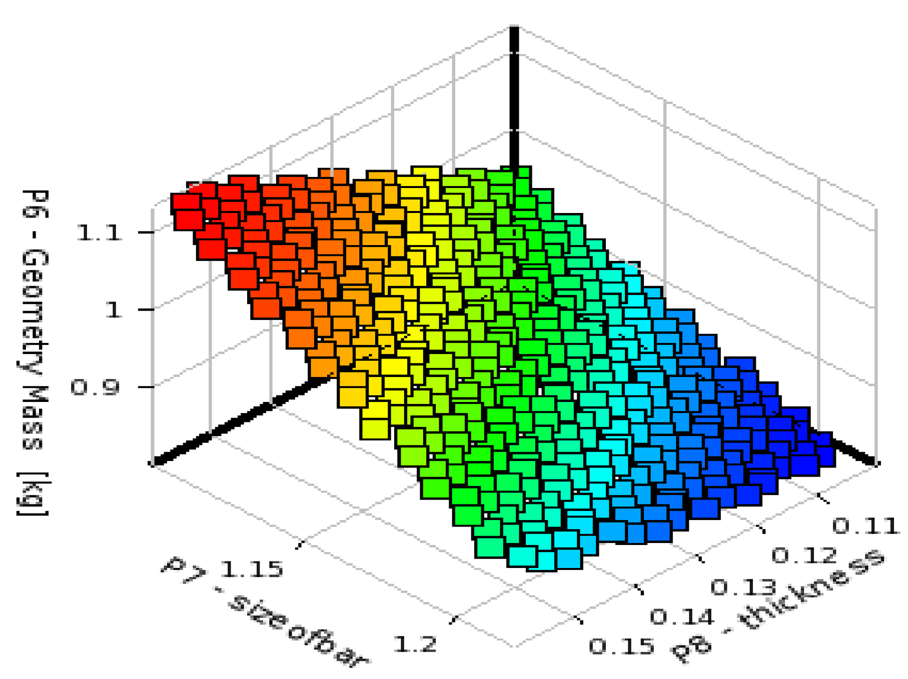

Fig.5 Tradeoff of mass

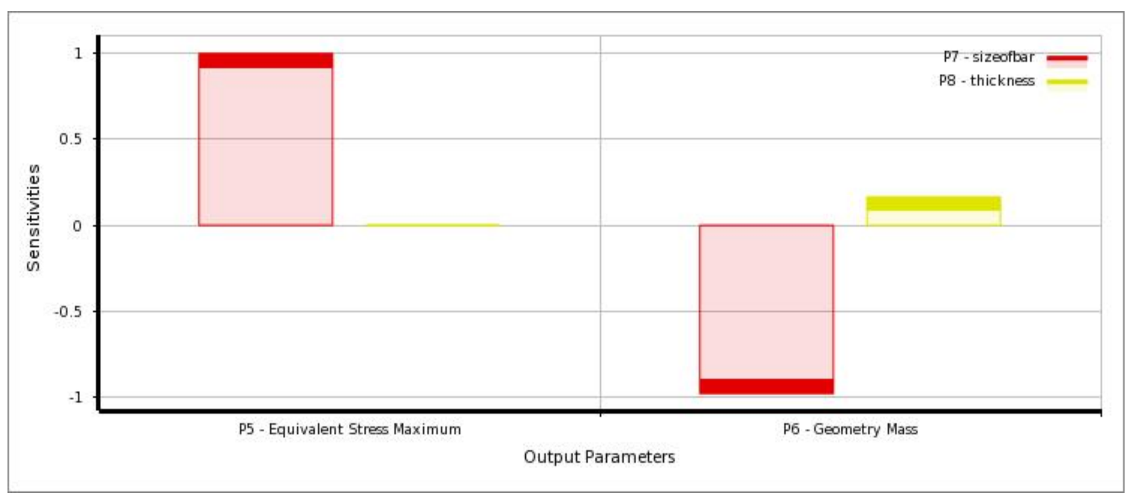

Fig.6 the sensitivities of all parameters

The result of this simulation is shown below. The maximum Equivalent (von-Mises) stress is 5.02×10^8Pa (502Mpa), which means the yield stress of the selected material must larger than 502 Mpa. Design

Conclusion

In this project, the selection of the best material and manufacturing process was shown. And the size of the bar structure was designed by finite element method. The ANSYS was used to simulate the bar structure . The maximum Equivalent (von-Mises) stress , Tradeoff of the parameters and sensitivities of all parameters were shown. By this optimization, the mass was reduced 0.35kg (about30%).